

Low loss photonic components in high index bismuth borate glass by femtosecond laser direct writing

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Abstract: Single mode, low loss waveguides were fabricated in high index bismuth borate glass by femtosecond laser direct writing. A specific set of writing parameters leading to waveguides perfectly mode matched to standard single-mode fibers at 1.55 μm with an overall insertion loss of ~ 1 dB and with propagation loss below 0.2 dB/cm was identified. Photonic components such as Y-splitters and directional couplers were also demonstrated. A close agreement between their performances and theoretical predictions based upon the characterization of the waveguide properties is shown. Finally, the nonlinear refractive index of the waveguides has been measured to be $6.6 \times 10^{-15} \text{ cm}^2/\text{W}$ by analyzing self-phase modulation of the propagating femtosecond laser pulse at the wavelength of 1.46 μm . Broadening of the transmitted light source as large as 500 nm was demonstrated through a waveguide with the length of 1.8 cm.

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OCIS codes: (320.7130) Femtosecond phenomena; (130.2755) Integrated optics devices.

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1. Introduction

In recent years, modification of refractive index with ultrafast lasers irradiation has attracted a lot of interest due to a wide range of applications including three-dimensional photonic devices, optical data storage, nanostructures and bio-photonic components in a variety of transparent materials [1-14]. Glasses with low linear (n_0) and nonlinear (n_2) refractive indices, such as fused silica, have been used in the majority of femtosecond laser direct writing experiments. There are only few reports on the femtosecond laser direct writing in high index glasses such as SF57, chalcogenide and heavy metal oxide glasses having $n_0 > 1.8$ and $n_2 > 10^{-15} \text{ cm}^2/\text{W}$ [15-18].

Bismuth borate glass possesses a large n_2 value ($5 \times 10^{-15} \text{ cm}^2/\text{W}$ at 1064 nm) which is almost 20 times higher than the nonlinear refractive index of silica glass [19]. This makes it an excellent candidate material for the fabrication of nonlinear optical devices such as optical switches or supercontinuum generators. Moreover, thermal poling can induce high second-order nonlinearity in bismuth borate glass [20], which can be used for fabricating nonlinear optical devices such as frequency converters or electro-optic modulators [14]. Despite these advantages, the implementation of passive waveguide components in bismuth borate glass using femtosecond laser direct writing is still unexploited.

In this paper, a detailed characterization of optical waveguides fabricated in high index bismuth-borate glass using femtosecond laser direct writing is presented. The fabricated waveguides show markedly improved insertion and propagation losses, compared to other results in high index glass [15-17]. Passive waveguide components as well as large spectral broadening were also demonstrated opening new opportunities for realizing embedded nonlinear all-optical devices in a glass chip.

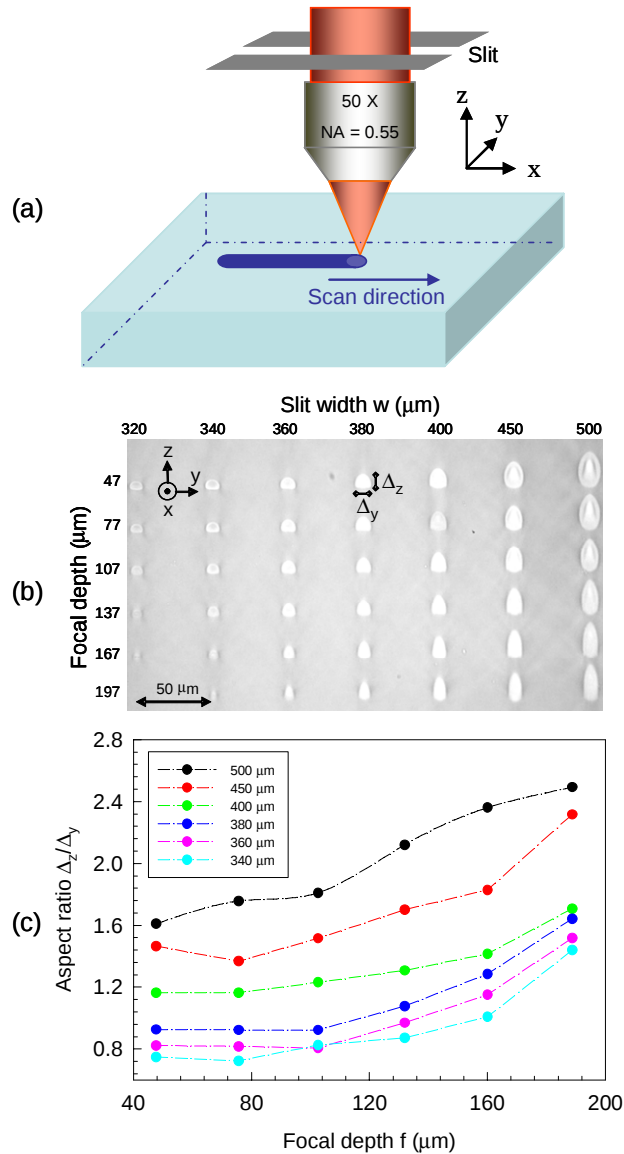


Fig. 1. (a): Schematic of the writing process. (b): Microscope image of the waveguides in the yz plane. (c): Aspect ratio versus focal depth using various slit widths.

2. Waveguides fabrication

Within the bismuth-borate glass family, an experimental glass (BZH7) produced by Nippon Sheet Glass Co. Ltd, having nominal composition of $12.5\text{Bi}_2\text{O}_3\text{-}43.75\text{ZnO-}43.75\text{B}_2\text{O}_3$ (mol %), was chosen. Glass plates of $30\text{ mm} \times 20\text{ mm} \times 0.5\text{ mm}$ were used as substrates.

The laser radiation was produced by a regeneratively amplified mode-locked Ti: sapphire laser system (Coherent RegA 9000) delivering pulses of 150 fs at 800 nm with a 250 kHz repetition rate. The collimated laser beam was focused via a 50X objective ($\text{NA} = 0.55$) beneath the input surface of the sample at various depths, ranging from 30 μm to 200 μm . The sample, mounted on a computer controlled xyz stage, was translated along the x-axis perpendicular to the propagation direction of the laser beam (z-axis - Fig. 1(a)). The scanning speed was 200 $\mu\text{m/s}$. The polarization of the laser beam was linear and its direction was set orthogonal to the writing direction using a half-wave plate. The pulse energy (E_p) was varied from 12 nJ to 1 μJ using a neutral density filter.

The advantage of the transverse writing geometry is that it allows the fabrication of waveguides with length and shape limited only by the sample dimensions. However, this writing geometry causes an intrinsic asymmetry of the waveguide cross section [21]. Several techniques, including the astigmatic cylindrical telescope [21], multiple scan [22] and slit beam shaping methods [23] have been proposed in the literature to overcome this issue. The latter was implemented in our experiment by inserting a slit oriented parallel to the writing direction (x-axis) close to the focusing objective lens (Fig. 1(a)).

3. Waveguides characterization

3.1 Waveguide cross-section

In order to determine the optimum slit width for fabricating waveguides with circular cross-sections, groups of channels were written at the same pulse energy but with slit widths ranging from 320 μm up to 500 μm . After irradiation, the sample was side-polished and checked under an optical microscope in transmission mode (Fig. 1(b)). For each column, the channels were fabricated using the same slit width and for each row the structures were irradiated at the same focal depth. The aspect ratio Δ_z/Δ_y (Fig. 1(b)) decreased from 1.6 to 0.7 by reducing the slit width from 500 μm down to 340 μm at the focal depth of 47 μm (Fig. 1(c)). By using a 380 μm slit, a nearly symmetric structural modification with the dimension of $\sim 10\text{ }\mu\text{m}$ was achieved (Fig. 1(b)). Moreover, for a constant slit width, the aspect ratio is preserved up to focal depths of $\sim 100\text{ }\mu\text{m}$ (Fig. 1(c)). Beyond this value, the effect of spherical aberration is not negligible thus leading to an increase of aspect ratio. A cover-slip corrected objective with designed focal depth could be used to minimize this effect extending the focal depth range in which circular waveguides can be made.

3.2 Mode-field diameter

Near-field mode profiles of the waveguides were obtained by coupling 1.55 μm light into the waveguides using fiber butt coupling and by imaging the waveguides output facets with an Electrophysics-7290 camera using a 20X objective lens ($\text{NA} = 0.3$). As an example, a typical circular mode-profile for a single mode waveguide, fabricated with a 400 μm slit, 200 $\mu\text{m/s}$ scan speed and 200 nJ pulse energy, is shown in Fig. 2(a). The $1/e^2$ mode field diameter (MFD) is measured to be 11 μm with the aid of a beam analysis system (BeamView Analyzer). The MFD of this waveguide matches well the one of standard SMF-28 fiber having 10.4 μm MFD at 1.55 μm , therefore low insertion losses can be anticipated for this particular waveguide.

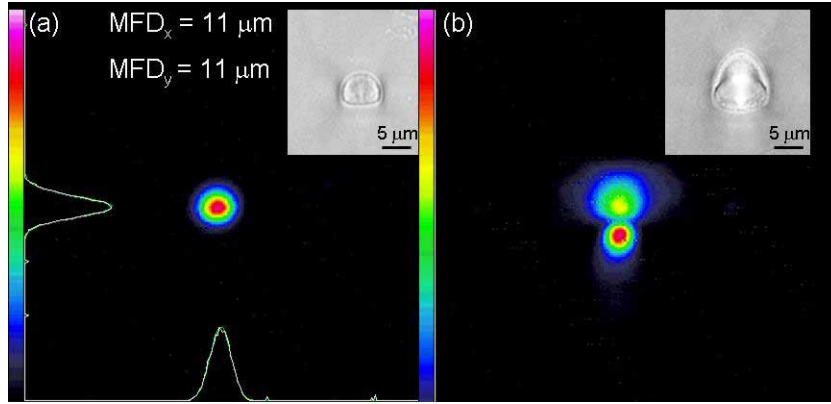


Fig. 2. Near-field mode profiles of the waveguides at 1.55 μm and (insert) microscope images of the waveguide cross-section. (a): $E_p = 200$ nJ, $w = 400$ μm . (b): $E_p = 280$ nJ, $w = 500$ μm .

For all the waveguides fabricated in the parameter range of this study, single mode operation at telecom wavelengths was initially checked by changing the coupling conditions and ensuring that higher-order modes could not be excited. This preliminary screening allowed us to conclude that single mode waveguides in BZH7 glass can only be achieved over a narrow range of processing pulse energy, from 160 nJ to 240 nJ.

Direct confirmation of the above conclusion was provided by measuring the numerical aperture (NA) of the single mode waveguides using the beam analyzer and by estimating the normalized frequency or V-number which is defined as $V = (2\pi/\lambda)a\text{NA}$ (where “a” is the radius of the waveguides). The core radius was obtained from visual imaging of the waveguide cross-section under a calibrated optical microscope (Fig. 2 - inserts). By assuming a step-index profile of the waveguide cross-section, the refractive index change Δn at 1550 nm was estimated from the measured NA value through the relation of $\text{NA} \approx (2n\Delta n)^{1/2}$ (where $n = 1.8$). Our results show that both Δn and V increase while increasing the pulse energy, E_p , from 160 nJ to 280 nJ (Fig. 3). For pulse energies below or equal to 240 nJ it can be seen in Fig. 3(b) that the V number is below 2.405, thus indicating single mode operation and confirming our previous observation. Δn reaches the maximum value of 4.5×10^{-3} yielding a V-number of 2.7 (Fig. 3(b)) and therefore multimode operation (Fig. 2(b)), when using a 500 μm slit and 280 nJ pulse energy.

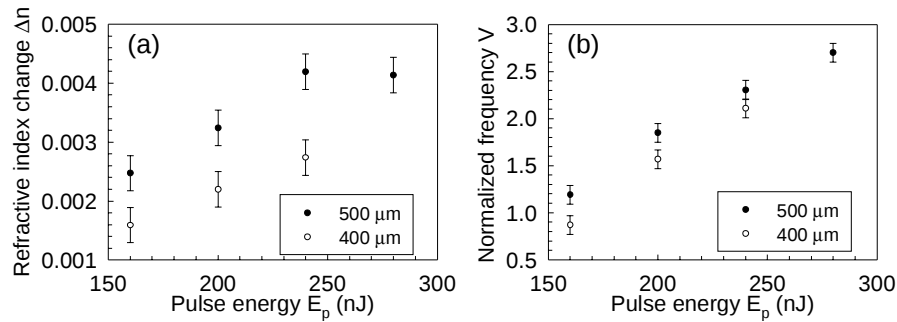


Fig. 3. (a): Refractive index change of the waveguides fabricated using 400 μm and 500 μm slits versus pulse energy. (b): Normalized frequency of the waveguides versus pulse energy.

3.3 Insertion loss

Waveguide insertion loss measurements were performed using an external cavity tunable diode laser (Photonetics Tunics-Plus) operating in the 1.3 – 1.6 μm wavelength range. The laser beam was launched into an SMF28 single mode fiber butt coupled to the waveguides, and collected using a 10X (NA = 0.25) objective. The insertion loss was obtained from the power measured at the output waveguide facet normalized to the power at the input facet. The total insertion losses, measured at 1.55 μm for the 1.8 cm long waveguides are given in Table 1. The waveguide fabricated using the 400 μm slit, 200 nJ pulse energy and 200 $\mu\text{m/s}$ scan speed exhibits an insertion loss of only 1 dB. Such a small value results from the circular mode profile which is perfectly mode matched to the single mode fiber (SMF28) and from the small propagation loss (See section 3.2 and fig. 2a). The insertion loss of 1dB compares favorably to the reported value of 0.7 dB/cm for the propagation loss in waveguides written in high index glass [15].

3.4 Propagation loss

Since Fresnel reflections at the interfaces accounts for 0.36 dB, or 8% loss, per facet, an upper bound of the propagation loss, can be estimated. The results, where this method yields accurate measurements, are reported in Table 1. The error of 0.40 dB/cm arises from three main contributions: the coupling loss error; the 1% fluctuation of the laser power and the error of 2.7% in the effective refractive index (n_{eff}).

The insertion loss method provides good estimates for the propagation loss, α , when $\alpha L < 0.3$ (or $\alpha > 0.74$ dB/cm for our waveguides of $L = 1.8$ cm) [24]. However, the best waveguides fabricated in this work appear to show propagation loss below 0.25 dB/cm ($\alpha L < 0.1$). Such values are known to be particularly challenging to be measured and high accuracy can only be achieved with the Fabry-Perot method [24, 25].

Slit Size (μm)	Pulse Energy (nJ)	Total Insertion Loss (dB)	Propagation Loss (dB/cm)
300	200	6.93 ± 0.17	$3.49 \pm 0.40^{(a)}$
400	160	3.85 ± 0.17	$1.75 \pm 0.40^{(a)}$
400	200	0.98 ± 0.17	$0.21 \pm 0.14^{(b)}$
400	240	2.16 ± 0.17	$0.80 \pm 0.40^{(a)}$
400	280	1.70 ± 0.17	$0.48 \pm 0.14^{(b)}$
500	160	1.45 ± 0.17	$0.46 \pm 0.12^{(b)}$
500	200	1.37 ± 0.17	$0.18 \pm 0.05^{(b)}$
500	240	1.79 ± 0.17	$0.71 \pm 0.22^{(b)}$

Table 1: Total insertion loss and propagation loss for different waveguides. The length of the waveguides is 1.78 cm. The propagation loss is obtained from either (a) insertion loss measurements or (b) Fabry-Perot method.

The Fabry-Perot method owes its name to the fact that a waveguide is considered as a low-finesse symmetric resonator where the end-faces act as mirrors. By varying the wavelength of the input light source, the transmission of the waveguide cavity reaches periodic maxima (I_{max}) and minima (I_{min}). The propagation loss of a waveguide is then calculated according to Eq. (1), where $k = I_{\text{min}}/I_{\text{max}}$, is the modulation ratio, $R = [(n_{\text{eff}} - 1)/(n_{\text{eff}} + 1)]^2$ is the facet effective reflectivity and L is the length of the waveguides:

$$\alpha [\text{dB/cm}] = \frac{4.343}{L} \ln \left(R \times \frac{1 + \sqrt{k}}{1 - \sqrt{k}} \right) \quad (1)$$

One advantage of this method is that it is independent on the value of the coupling losses. Moreover, the effective index, n_{eff} , can be directly calculated from the free spectral range

$\Delta\nu$ of the cavity which is defined as $\Delta\nu = c/(2n_{\text{eff}}L)$, where $L = 1.7739 \pm 0.0001$ cm. In order to perform the loss measurement care has been taken while polishing the endfaces to ensure the parallelism between the two facets. The inclination was below 0.03 degrees for all the waveguides. The external cavity tunable diode laser, mentioned earlier for the characterization of the insertion loss, was also employed in the Fabry-Perot measurement as it guarantees a sufficiently narrow linewidth. The wavelength of the laser source was scanned from 1550 to 1550.4 nm in steps of 0.001 nm, which is the smallest step allowed by the instrument. The waveguide output power was recorded as a function of the input wavelength and a typical output of the measurement, relative to the waveguide written at 200 nJ pulse energy using a 500 μm slit, is given in Figure 4. Equally well-resolved fringes were obtained for the other waveguides albeit with different fringe visibility. The results summarized in Table 1 show very good reproducibility. Overall, agreement between the insertion loss and the Fabry-Perot method is obtained with the former giving better results for higher attenuations and the latter being more suited to characterize low-loss waveguides. The measurement of the waveguide written at 200 nJ pulse energy using a slit aperture of 400 μm showed the remarkably small propagation loss of 0.21 ± 0.14 dB/cm in agreement with the indications obtained from the insertion loss measurement. The relatively large error is intrinsic of the Fabry-Perot method when applied to such low-loss waveguides. The reason can be understood from Eq. (1) by noting that the percentage error $\delta\alpha/\alpha$ comes close to infinity as α approaches zero [24]. Another waveguide, written with the same pulse energy but with 500 μm slit width, showed a comparable attenuation but the error was greatly reduced by weighted average on several measurements. Further reduction of the error could be achieved by mirror-coating the waveguide end-faces to enhance the cavity finesse or by fabricating longer waveguides [24]. Within experimental errors, no polarization dependent loss was observed which comes as a direct consequence of the good circularity of the waveguides cross-section.

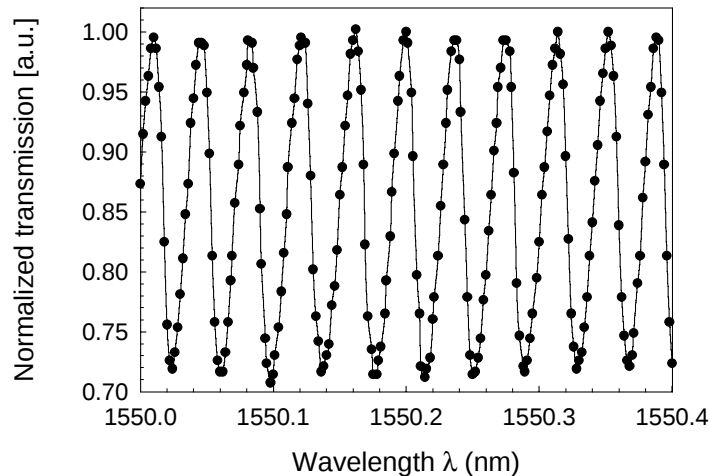


Fig. 4. Fabry – Perot loss measurement of the waveguide ($E_p = 200$ nJ, $w = 500$ μm) at 1550 nm.

4. Optical components

Passive optical components in BZH7 glass, such as splitters and directional couplers were also fabricated and characterized.

4.1 Y-splitters

50:50 Y-splitters embedded in bismuth borate glass plates were written at the pulse energy of 200 nJ and scan speed of 200 $\mu\text{m/s}$ using 300 and 500 μm slits. The Y-splitters are composed of an input port continued by an 8 mm long straight waveguide that splits into two separate branches diverging from each other by an angle α over a length of 5 mm (Fig. 5(a)). For each set of writing conditions the angle α was varied between 0.4° and 2.0° in steps of 0.4° . A 50:50 splitting ratio at 1.55 μm was obtained for all the structures. The Y-branch having $\alpha = 0.4^\circ$ and written using the 500 μm slit displayed the minimum insertion loss of 1.8 dB. Differential interference contrast image of the Y-splitter is given in Fig. 5(b). The 50:50 splitting ratio at 1.55 μm wavelength can be appreciated from the output near-field distribution of the Y-splitter (Fig. 5(c)).

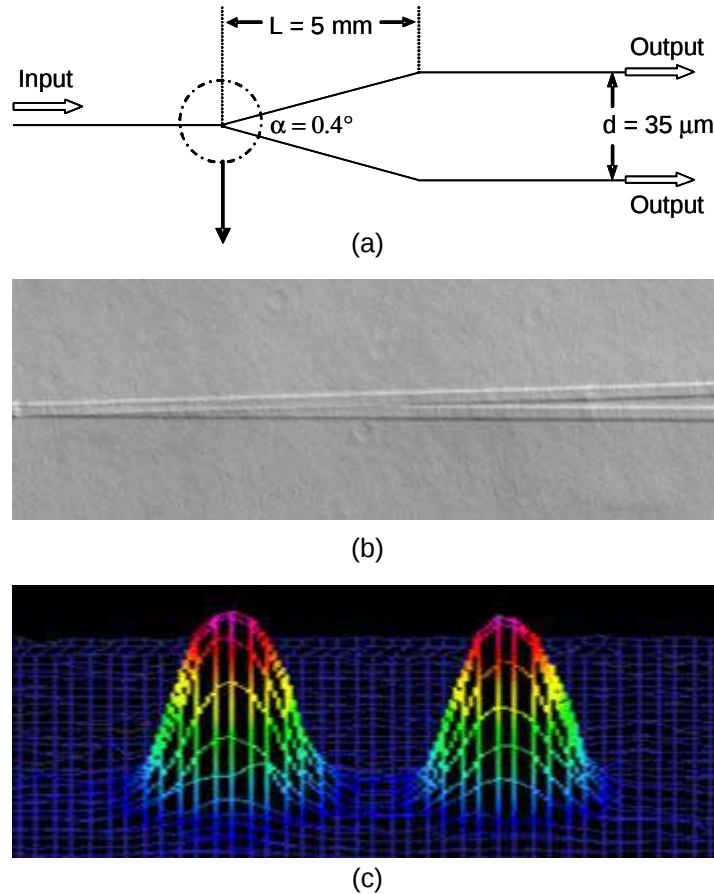


Fig. 5. (a): Schematic of the Y – splitter ($E_p = 200 \text{ nJ}$, $w = 300 \mu\text{m}$) (b): Differential interference contrast image of splitting part of the Y – splitter. (c): Near-field mode profile of the output facet of the Y-splitter from launching 1.55 μm light.

4.2 Directional couplers

Directional couplers with various coupling ratios were fabricated at 200 nJ pulse energy and 200 $\mu\text{m/s}$ scan speed with slit aperture of 300 μm (Figure 6). Different coupling ratios γ , defined as $P_4 / (P_2 + P_4)$, could be obtained by varying the center-to-center distance, d , between the two arms. Coupling ratios ranging from 10%, for $d = 30 \mu\text{m}$, up to 90%, for $d = 15 \mu\text{m}$,

were demonstrated. The coupling ratio was also calculated using the BeamProp software (RSoft) based on beam propagation method (BPM). The values of the refractive index difference and waveguide radius measured earlier (see section 3) were used in the simulation. The result of the computation, which is based upon experimentally measurable quantities without employing any free-parameter, is in excellent agreement with the experimental data (Fig. 7).

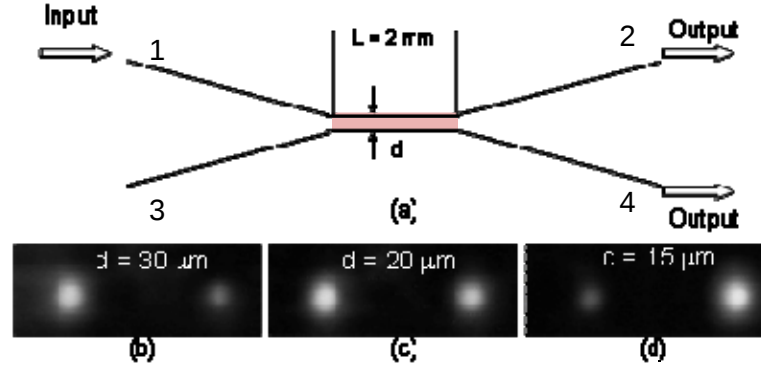


Fig. 6. (a): Schematic of directional coupler ($E_p = 200$ nJ, $w = 300$ μm). Near-field mode profiles of the output facets of the directional couplers when the centre-centre distance d equals (b): 30 μm . (c): 20 μm . (d): 15 μm .

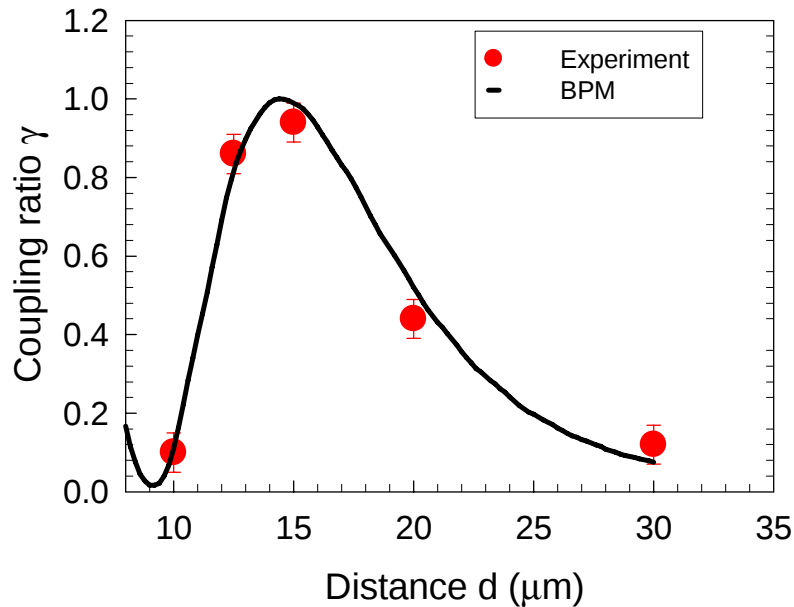


Fig. 7. Coupling ratio γ against center-center distance d .

5. Characterization of second- and third-order optical nonlinearities

Finally the potential of photonics components in BZH7 glass for non-linear optical applications such as for supercontinuum generation is assessed by measuring the non-linear refractive index n_2 . A Ti:sapphire OPA system emitting pulses of ~ 150 fs at 1.46 μm with 250 kHz repetition rate was used for this purpose. A linearly polarized laser beam was coupled into the waveguide by a 4X microscope objective (NA = 0.12). The transmitted light

was then collected by a 10X objective (NA = 0.3) and coupled into an optical spectrum analyzer using a multimode fiber. The largest spectral broadening was observed in the waveguide written with 240 nJ and a 500 μm aperture. As the peak power in the waveguide was increased, the output spectrum broadened up to 500 nm corresponding to a phase shift of approximately 8.5π . This broadening is due to self-phase modulation of propagating light inside the waveguide with average power of only 2.0 mW [26]. No index modification was induced which was confirmed by the linear dependence of the output power versus the input power. The nonlinear refractive index n_2 of the waveguide was estimated to be $(6.6 \pm 0.5) \times 10^{-15} \text{ cm}^2/\text{W}$, which is comparable to the reported value of $5 \times 10^{-15} \text{ cm}^2/\text{W}$ at 1064 nm for the bulk bismuth-borate sample [19] and about 20 times higher than the n_2 of fused silica.

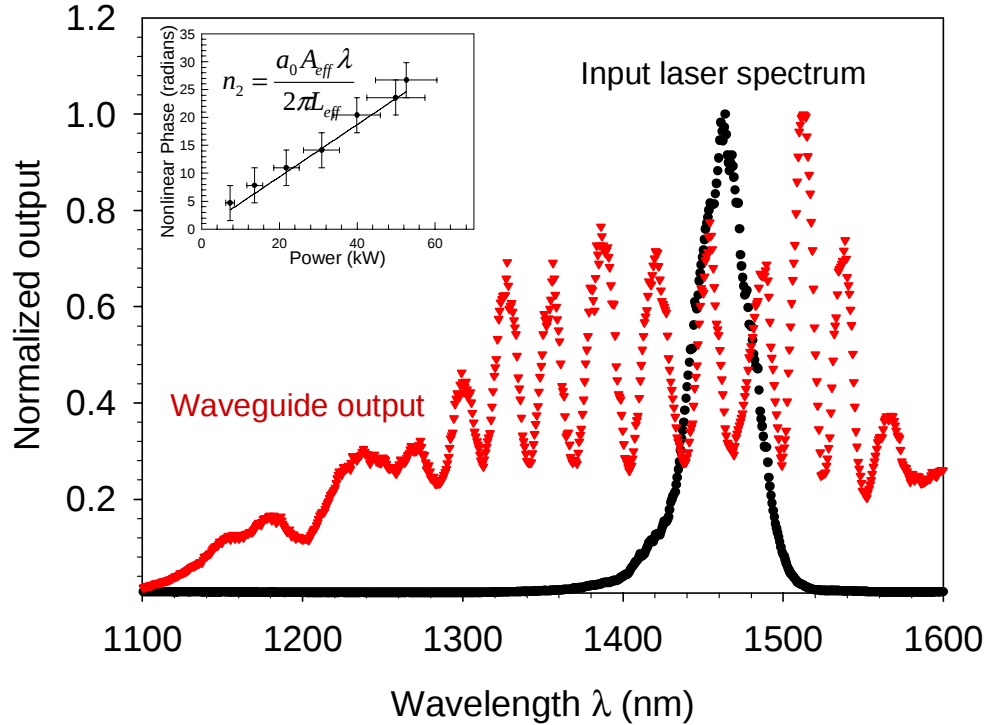


Fig. 8. Normalized spectrum of the input pulse (black) and spectrum of the pulse (red) collected after propagation through the waveguide ($E_p = 240 \text{ nJ}$, $w = 500 \mu\text{m}$).

Preliminary experiments were carried out on thermal poling of the fabricated waveguides and to investigate the effect of the femtosecond laser induced modifications on the second-order nonlinearity ($\chi^{(2)}$) produced by poling in bismuth glass. The thermal poling was carried out at 290 $^{\circ}\text{C}$ for 5 minutes at a constant current of 100 μA [27]. The second-order nonlinearity of $\chi^{(2)} = 0.8 \text{ pm/V}$ was measured using the Maker's fringe technique. The spatial overlap between the guided mode in the waveguides and the second-order nonlinearity induced by poling was optimized by fabricating a set of waveguides with different depth under the glass surface. The uniformly poled waveguides were then tested for evidence of second-harmonic generation (SHG) by launching 1064 nm radiation from a Q-switched (repetition rate 1 kHz, 200 ns pulse duration) and mode-locked (76MHz, 300 ps) Nd:YAG laser. The second harmonic (SH) signal was produced only in the waveguides buried less than 10 μm below the surface which was in agreement with the expected depth of the nonlinear region in our glass samples. The measured SH signal exhibited quadratic growth on the pump power (Fig. 9) and was about 3 times higher for the TM-polarized pump light compared to the

TE-polarized light. The deviation from theoretical ratio of the SH harmonic signals of 9:1 is commonly observed in poled waveguides [28]. Under the assumption that modal-phase matching was not taking place in the waveguides, the SHG efficiencies for the waveguide and the bulk geometries were compared. In the bulk geometry the pump light was focused on the surface of a uniform region of the poled sample between the waveguides. After scaling the power densities for the two geometries and considering that the nonlinear interaction takes place at a coherence length, the values of the second-order nonlinear coefficient were found to be the same for the femtosecond laser written waveguide and for the bulk of the glass. Since in poled glass, $\chi^{(2)} = 3\chi^{(3)}E_{dc}$, where E_{dc} is the frozen-in field, this result indicates that the third-order nonlinearity in BZH7 glass is not affected by the femtosecond laser writing process as it was concluded from the n_2 measurements presented above.

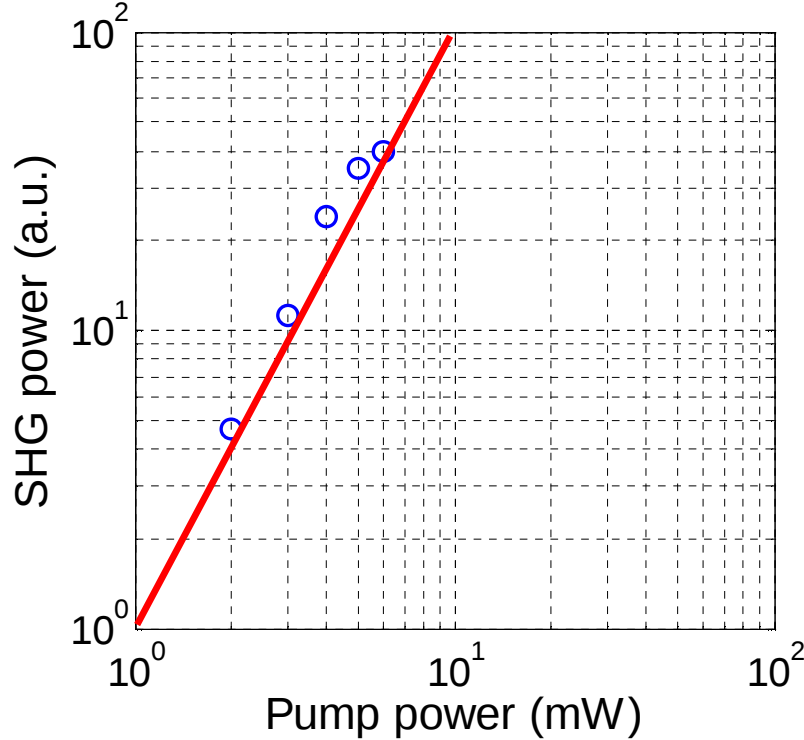


Fig. 9. Quadratic dependence of the SHG power against the fundamental pump power.

6. Conclusion

Low loss, polarization insensitive, single mode waveguides with circular mode profiles and refractive index changes of 4.5×10^{-3} were inscribed by ultrafast laser radiation in high index bismuth-borate glass. Insertion loss of only 1 dB and propagation loss of 0.2 dB/cm at 1.55 μm were demonstrated. Y-splitters and directional couplers were also fabricated and their performances closely agree with theoretical simulations based upon experimentally measurable quantities obtained from the waveguide characterization. Moreover, a 500 nm spectral broadening was obtained by launching less than 2.0 mW average power (53 kW peak-power) of 150 fs laser pulses at 1.46 μm through the waveguides. The broadening and quality of the supercontinuum could be further increased by pumping closer to the zero-dispersion wavelength. In our case the supercontinuum is mainly caused by self-phase modulation allowing to estimate a nonlinear refractive index n_2 of $\sim 6.6 \times 10^{-15} \text{ cm}^2/\text{W}$ which is in agreement with published data [19]. Preliminary experiments on the uniformly poled

waveguides show the same $\chi^{(2)}$ value as the bulk glass. Further experiments to implement quasi-phase-matching in periodically poled waveguides are in progress. Femtosecond laser written low loss waveguides with large n_2 are attractive for fabricating nonlinear glass based devices.

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